ECE 398 – INTRODUCTION TO QUANTUM SYSTEMS

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This is a course proposal for a modified version of ECE 487 to be offered in Spring 2022. Compared to ECE 487, this course will be more introductory in its scope and cover fewer topics but with greater depth. Its primary objective is to provide the conceptual and quantitative foundations for higher-level courses in quantum information science and nanoelectronics.

Motivation

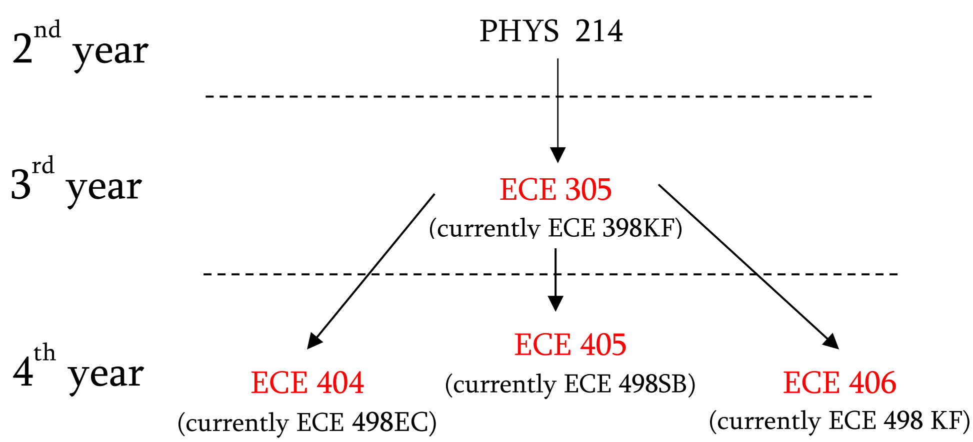
Quantum information science (QIS) is a rapidly developing field that cuts across ECE, physics, CS, and math. There is currently a charge from industrial and governmental agencies to train the next generation of "quantum literate" scientists. Complementing this "top-down" demand is a growing cohort of students who want to take QIS courses and enter the QIS workforce after graduation.

Currently, ECE students take PHYS 214 as their primary introduction to quantum mechanics, and their next exposure is at the 400-level. Hence, there is a large conceptual and mathematical gap between the 200- and 400-level courses, which makes it difficult for students to learn the higher-level material. We propose to fill this gap by offering a 300-level course that replaces ECE 487 and naturally flows into three 400-level topics courses in QIS (ECE 498EC: Quantum Information Processing and Communication; ECE 498KF: Quantum Optics and Devices; ECE 498SB: Manipulation of Elementary Quantum Systems).

Course Placement

This course is designed to be taken in the second semester of a typical student's third year with PHYS 214 as prerequisite. Its direct sequel will be Quantum Systems II (currently offered as ECE 498 SB). Essentially, this proposed course covers the first part of ECE 498SB in more detail. By having this material offered in a separate course, ECE 498SB could then focus on more advanced topics. This ECE 398 course will also provide the foundation for ECE 498EC in terms of understanding bra/ket notation and qubits, as well as for ECE 498KF in terms of understanding the quantum harmonic oscillator and light-matter interaction.

It is hoped that this temporary course will ultimately become permanently listed as ECE 305. The **Quantum Systems sub-discipline** in ECE would then consist of the following course sequence:



Scope of the Course and Learning Objectives

This course consists of three main components:

1. **Foundations** (11 lectures). The first part of the course will focus on the principles and mathematical formalism of quantum mechanics, such as Schrödinger's equation, bra/ket notation, quantum measurement, and the quantum harmonic oscillator. As a conceptual learning objective, the student should understand how quantum systems can be represented by vector spaces and the difference between finite and infinite-dimensional quantum systems. There will be some overlap with PHYS 214, but a greater emphasis will be placed on understanding these principles from a computational perspective, i.e. identifying two-level systems as qubits, interpreting Hamiltonian evolution in terms of logical gates, and treating quantum measurement as a process of acquiring read-out data.

2. **Perturbations and Light-Matter Interaction** (9 lectures). The second part of this course will explore elementary perturbation theory and its applications. A semi-classical approach will be taken to study how a quantized atom interacts with a classical electromagnetic field. This will allow the student to learn some of the basic physical principles underlying quantum technologies such as atomic absorption/emission, Rabi oscillations, and optical Bloch equations. As a conceptual learning objective, the student should understand the difference between classical, semi-classical, and fully quantum descriptions of light-matter interaction.

3. **Atomic Qubits and Quantum Information Applications** (7 lectures). The third part of this course will focus on quantum information processing, and it will set the stage for more advanced courses (eg. ECE 405, 406, 407). Having developed an understanding of atomic quantization and transitions, the student will study the two-level atomic system as one physical realization of a qubit. The density matrix and the Bloch vector representation of states will be introduced. As a conceptual learning objective, the student should understand the meaning of quantum entanglement and how it leads to decoherence in many-body systems.

   As a final sequence in the course, the student will learn some of the basic concepts and protocols in quantum computing and communication. The quantum circuit model will be covered along with the Deutsch-Jozsa algorithm as an example of a quantum computing advantage. The student will also be introduced to quantum entanglement and shown how it is a key resource for performing many quantum information tasks such as quantum teleportation. As a conceptual learning objective, the student should be able to describe how quantum teleportation does not violate the principles of special relativity (i.e. faster than light communication).

Course Syllabus:

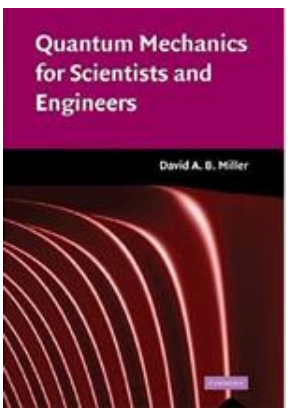
Course Instructor (for FA 2022):
Dr. Kejie Fang
2112 MNTL
Kfang3@illinois.edu

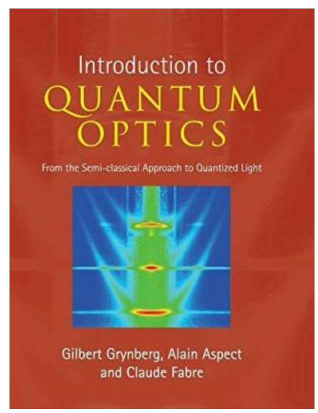
Course website:
https://courses.grainger.illinois.edu/ece398kf/fa2022/

Office Hours:
TBA

Lectures:
Tues/Thurs, 03:30PM - 04:50PM

Textbooks:
D. Miller, Quantum Mechanics for Scientists and Engineers, Cambridge, 2008.
G. Grynberg, A. Aspect, C. Fabre, *Introduction to Quantum Optics*, Cambridge, 2010.





Lecture notes will be posted on Canvas course webpage

Homework, Exams, and Grading:
This course will have **homework assignments given every two weeks**, two midterm exams, and a final exam. Their relative contribution to the overall grade is as follows:

Homework	25%
Midterm Exams 1 &2, Final Exam	25% each

Course Outline:

	Topics	Subtopics	Lectures
Part I	**Foundations** (Griffiths Chpt. 2, Miller Chpt. 2/3)	1. Time-dependent and time-independent Schrödinger's equation; solutions in different potentials	**1-3**
		2. Hilbert space, finite vs. infinite-dimensional systems, bras/kets, quantum numbers, qubits and qudits	**4**
		3. Quantum measurements, observables, uncertainty relation, Pauli measurements	**5-6**
		4. The quantum harmonic oscillator; Dirac solution, coherent states, squeezed states	**7-8**
		5. The quantum circuit model, gates, measurements	**9-10**
		6. Review and problem solving	**11**

Midterm Exam 1	**12**

	Topics	Subtopics	Lectures
Part II	**Perturbations and Light-Matter Interaction** (Miller Chpt. 6/7, GAF Chpt. 1/2)	7. Electric and magnetic dipole interactions, the Hamiltonian for a quantum particle in a classical field	**13-14**
		8. Time-independent perturbation theory	**15**
		9. Time-dependent perturbations; pulses and oscillating perturbations, Fermi's Golden Rule	**16-17**
		10. Two-level systems, Rabi Oscillations	**18-19**
		11. Optical Bloch equations	**20**
		12. Review and problem solving	**21**

Midterm Exam 2	**22**

	Topics	Subtopics	Lectures
Part III	**Atomic Qubits** (Miller Chpt. 14, GAF Chpt. 2)	13. Density matrices, Bloch sphere	**23-24**
		14. Decoherence and coherent manipulations	**25**
	Quantum Information Applications	15. Quantum entanglement generation and characterization	**26**
		16. Quantum algorithms	**27**
		17. Quantum superdense coding and teleportation	**28**
		18. Quantum key distribution	**29**

Final Exam	**30**